Chapter 10
The Next-Generation Deep Space Network

This monograph has presented a comprehensive summary of all the large ground antennas in the Deep Space Network (DSN), including the evolutionary paths that have led to the current operational configuration. In this chapter, future scenarios are considered for both short-term and long-term needs.

A key element of the DSN, the 70-m antennas were built starting in the mid-1960s. They first became operational as 64-m antennas starting in 1966 and continued until 1973. They were extended to 70 m in support of the Voyager spacecraft encounter with Neptune in 1989. The original 64-m antenna had a design service life of 10 years for mechanical components, based on 25 percent use. Though life-extension efforts continue, recent failures and repairs indicate that extended outages can be expected. For example, on August 14, 2001, the radial bearing failed on the 70-m antenna at Goldstone, causing the antenna to be out of service for 4 days. Future catastrophic failures are possible, but not predictable.

The 70-m antennas are nonresilient, single points of failure. In 1991, the National Aeronautics and Space Administration (NASA) established a 70-m backup plan that uses four 34-m beam-waveguide (BWG) antennas per DSN complex to replace the downlink capability of a 70-m antenna [1]. This plan was only partially completed due to lack of funding.

In 1999, a 3-year study was commissioned to (a) investigate and estimate the remaining service life of the existing 70-m antennas and (b) investigate alternatives for backup and eventual replacement of the 70-m subnetwork capability. Some preliminary results from the study are discussed below.

However, there needs to be a look far beyond just the replacement of the 70-m antennas. The support of NASA's four major space science themes (Structure and Evolution of the Universe, Origins, Solar System Exploration, and the Sun-Earth Connection) demands a much greater DSN capability to support high-data-rate science instruments such as synthetic-aperture radar and multispectral and hyperspectral imagers. In addition, video or high-definition television (HDTV) can provide greater data return for public outreach from Mars missions.

Three complementary technologies need to be explored to fulfill these needs: (a) significantly larger (10 to 100 times) antenna aperture size in the DSN, (b) optical communications, and (c) relay satellites orbiting nearby planets.

10.1 The Study to Replace 70-Meter Antennas

The DSN 70-m antennas are crucial for deep-space critical events, both for planned operations and anomalous unplanned operations. Examples of critical planned operations are encounters, entry-descent-landing (Mars missions), limited-life vehicles (Solar Probe [to the Sun] and Europa [to Jupiter] missions), and limited data-return span (Cassini [to Saturn] high-activity periods and Near Earth Asteroid Rendezvous [NEAR] Eros descent). Examples of anomalous unplanned operations are spacecraft emergency recovery (Solar and Heliospheric Observatory [SOHO], NEAR, and Voyager [tour of the solar system]) and saving damaged missions [Galileo, to Jupiter]. Compared to 34-m antennas, the DSN 70-m antennas can significantly improve the data return of space science missions.

The 70-m antennas, if baselined, can produce a fourfold increase in mission data return (at any given frequency) or reduce mission power, mass, volume, and associated cost. But the 70-m antenna can only be baselined for a mission if it is reliable and backed up—hence, the need for the study to replace the 70-m antennas.

The replacement study considered the following options [2]:

- Extending the life of the existing 70-m antennas
- Designing a new 70-m single-aperture antenna
- Arraying four 34-m aperture antennas
- Arraying small reflector antennas
- Arraying flat-plate antennas
- Implementing a spherical pair of high-efficiency reflecting elements (SPHERE) antenna concept.

10.1.1 Extending the Life of the Existing 70-Meter Antennas

Two options were studied: life extension (a) with and (b) without a Ka-band upgrade.

A complete antenna structure model was updated for analysis of both strength and fatigue life, using the current antenna-use factor. The weakest sections were identified, and proposals for retrofitting the suspected areas were investigated. Items to be overhauled consisted of the subreflector positioner, azimuth drives, azimuth tangential links, azimuth bull gear, hydrostatic bearing, elevation bearing assembly, elevation bull gear, elevation drives, and the radial bearing assembly. Costs and tasks for both a 10-year and 25-year extension were identified.

New technology for adding Ka-band consisted of a new deformable subreflector with actuators; a much simpler, less expensive yet more accurate pointing instrument (replacement for the existing Master Equatorial precision pointing instrument); and a new X-/X-/Ka-band feed. If this option is selected, the X-/X-/Ka-band feed will replace the existing X-band feed and provide a Ka-band receive capability. The deformable subreflector will be used to compensate for gravity distortion at Ka-band.

10.1.2 Designing a New 70-Meter Single-Aperture Antenna

The new antenna design option includes state-of-the-art technology for gain recovery through gravity compensation and precision pointing at frequencies up to 50 GHz. This frequency range is sufficient to support the future Ka-band communication requirements and NASA's Human Exploration and Development of Space (HEDS) program. This design concept provides an increase in performance of the existing 70-m antennas. The primary configuration is for Ka-band (32 GHz) downlink and X-band downlink and uplink operations, with allowance for future expansion to include Ka-band uplink and HEDS radio frequency (RF) equipment. In addition, this antenna design would accommodate the existing 70-m antenna RF equipment, to the maximum extent possible, should the existing 70-m antennas become inoperable.

Key features of the new design are

- A 70-m-diameter main reflector
- Dual-shaped RF optics
- A center-fed BWG
- Feeds and front-end electronics located in alidade enclosures that rotate in azimuth
- Double elevation wheel and counterweights
- An electric drive for the azimuth wheels

- An actuated main reflector surface for gravity compensation
- A low-profile concrete foundation.

In addition, to provide precision blind pointing and focus corrections, the following technologies should be incorporated:

- Insulated and ventilated backup structure
- Thermal correction of pointing error and subreflector focus error
- Wind-sensor correction of pointing error and subreflector focus error
- A metrology-controlled subreflector.

10.1.3 Arraying Four 34-Meter Aperture Antennas

This configuration is an array of four 34-m BWG antennas to provide a 70-m equivalent aperture. This option is considered the most well understood, as the antenna cost is readily available from recent 34-m antenna construction. Throughout the 1980s, as part of the Voyager mission, development of downlink array technology was completed and tested for telemetry and tracking at the DSN facilities in Goldstone, California.

A problem was discovered when a high-power uplink (equivalent to 20 kW on the 70-m antenna) was considered. If this uplink effective isotropic radiated power (EIRP) was to be produced with a single 34-m antenna, a transmitter power of 80 kW would be required, and the power density in the near-field beam would exceed the aircraft safety standard of 10 mW/cm^2. The EIRP could be achieved with a lower power density if more than one antenna had a transmitter and the array was properly phased; the required EIRP could be produced by installing 5-kW transmitters on each of the four antennas. The proper phasing could be obtained by combining calibration of transmitter phase, using a spacecraft power monitor with knowledge of the geometric change in path length to each antenna as the pointing is changed. Atmospheric effects are small at X-band but are appreciable at Ka-band. Demonstration of X-band uplink phasing is being planned in the near future.

Future work was proposed to improve antenna performance for support of HEDS by providing

- A 100 percent solid reflector surface
- Lower reflector root-mean-square (rms) surface error
- Higher drive capacity to handle the additional wind load due to solid panel utilization
- Better antenna pointing requirements
- More reliable antenna design.

Developing and demonstrating an uplink arraying technique was also proposed.

10.1.4 Arraying Small Antennas

An array of three-hundred and fifty 6.1-m antennas is being constructed in Hat Creek, California, by the SETI (Search for Extraterrestrial Intelligence) Institute and the University of California, Berkeley [3]. The array is known as the Allen Telescope Array (after benefactor Paul Allen), is planned for completion in 2005, and will have the equivalent area of a 114-m-diameter single telescope. The antenna will utilize a log-periodic feed and low-noise amplifier (LNA) covering the entire 0.5- to 11.0-GHz frequency range.

A similar array, with one-hundred and forty 8-m antennas and higher-performance narrowband receivers at 2.2, 8.4, and 32 GHz, was considered for the 70-m replacement study. There are a number of advantages to this approach.

The first advantage is that, since the cost of an antenna varies with diameter (usually taken to be $D^{2.7}$), the cost per unit total area will be less with an array of small antennas. For example, if a 70-m antenna costs \$100 million, the cost of one hundred 7-m antennas will be $100 \leftrightarrow (0.1)^{2.7}$ = \$20 million. However, the cost of the electronics for the array will be higher. It can be shown [2] that the minimum total cost for a given total area will be achieved with an antenna cost that is 2.86 times the electronics cost. This ratio is dependent only upon the antenna cost exponent, here assumed to be 2.7.

The second advantage is that higher data throughput can be obtained by virtue of the flexibility and multiplicity of digital beam forming. Specifically, having multiple beams within the main beam of the small antenna allows simultaneous communication with multiple spacecraft orbiting a planet. Furthermore, subdividing the array into subarrays allows communication with a number of spacecraft located in different parts of the sky.

The third advantage is that the high reliability and availability are guaranteed by virtue of eliminating single-point failures. The array is sized to give the *G/T* and EIRP performance of a 70-m antenna, even when only 10 percent of the antennas are calibrated or maintained. And maintenance can be performed during a 40-hour workweek.

The fourth advantage is that very high angular resolution is ensured. Indeed, the proposed array has a beamwidth 14 times sharper than that of a 70-m antenna. The improved resolution allows new paradigms for determining spacecraft position. The beamwidth can be further sharpened by adding outrigger antenna elements.

The fifth advantage is extended frequency range. Small, stamped solid aluminum antennas can operate at short wavelengths much more easily than large structures. In fact, very wide bandwidth communication is feasible at frequencies as high as 100 GHz.

The required number of antennas to produce a 62.4-dB/K *G/T* at 8.4 GHz (70-m equivalent) as a function of diameter is shown in Table 10-1.

Table 10-1. Required number of antennas as function of diameter.

Minimum Performance Requirements	Antenna Diameter (m)		
	5	8	12
Elements required for 62.4-dB *G/T* at 8.4 GHz	328	128	58
Allowance for continuous calibration, 6 percent	20	8	4
Allowance for maintenance, 3 percent	10	4	2
Total required array elements	358	140	64

A number of primary enabling technologies are required to make a low-cost array feasible:

- Inexpensive, mass-produced, stamped parabolic dishes
- Multiple-frequency or decade bandwidth feeds
- Low-noise indium phosphide (InP) high-electron-mobility transistors (HEMT) amplifiers
- Commercially available 80-K cryogenics
- Wideband fiber-optic links
- Satellite transmitter and timing calibration
- Low-cost solid-state high-power amplifiers.

Whereas the technology for downlink arraying is quite well understood, the techniques for uplink arraying need to be developed.

10.1.5 Arraying Flat-Plate Antennas

This type of array consists of thousands of low-cost, flat-plate antennas arranged on the ground to enable signal detection from any direction within the hemisphere. The array orientation is optimized to maximize the signal-detection capability.

To provide a 70-m capability with active planar phased arrays, millions of elements are required. Many alternative phased arrays—including planar horizontal, hybrid mechanical/electronically steered, mechanically steered reflectors, multifaceted planar, planar reflect-arrays, and phased array-fed lens antennas—were compared and their viability assessed.

Although they have many advantages, including higher reliability and near-instantaneous beam switching or steering capability, the arrays are currently prohibitively expensive, and it has been concluded that the only viable array options at present are the arrays of modest-sized reflector antennas.

10.1.6 Implementing a Spherical Pair of High-Efficiency Reflecting Elements Antenna Concept

The original spherical pair of high-efficiency reflecting elements (SPHERE) concept consists of two 100-m nontipping spherical reflectors pointed at 30- and 70-deg elevation. The antennas are fully rotatable in azimuth, and switching between antennas is required as a spacecraft crosses 50-deg elevation. The 100-m-diameter provides a 70-m spot for all scans and, thus, nearly equivalent performance to a 70-m parabolic reflector. The concept utilizes an Arecibo Observatory (Puerto Rico)-style [4] Gregorian feed system, with a linear motion for elevation scan that covers a ± 20-deg elevation range. This concept has major cost advantages over more conventional structures:

- No tipping of the large structure
- No counterweight
- No gravity effects (thus permitting high-frequency operation)
- Simple alignment procedure
- Simple backup structure
- Identical, low-cost panels.

A spherical design was implemented in 1997 for the McDonald Observatory (Texas) 10-m optical Hobby–Eberly Telescope (HET) [5]. The cost of HET is significantly lower than that of an equivalently sized tippable structure such as the W. M. Keck Observatory (Hawaii) 10-m optical telescope.

The Chinese are also considering a spherical antenna [6]. They are proposing a 500-m sphere with adjustable main reflector panels and a simple focal-point feed. The main reflector panels are actuated to form a parabola for each direction of scan.

Additional work at the Jet Propulsion Laboratory (JPL) on the SPHERE concept [7] produced two significant improvements. First, the number of antennas was reduced from two to one by enlarging the aperture in the scan plane to 135 m and having the feed travel extended to the elevation angular range of 90 deg so the entire sky can be covered with just the one antenna. Second, the feed system was simplified from a two-mirror Arecibo-style system to a single-mirror system that is a phase-correcting subreflector.

A spherical antenna can potentially provide a large aperture at a much-reduced cost compared to that of conventional tipping antennas, and construction of such an antenna should, therefore, be vigorously pursued.

10.2 Towards the Interplanetary Network

For future exploration of Mars, Edwards [8] has proposed a communications and navigation infrastructure that includes orbiting relay satellites (see Fig. 10-1). The use of orbiting satellites around a planet to communicate with assets on the surface of that planet and to rely data back to Earth from the orbiter is a key element in an interplanetary network that may eventually include relays around the majority of planets.There are already two infrastructure assets (Mars Global Surveyor and 2001 Mars Odyssey) that can provide for some relay communications between the surface of Mars and Earth. There are also several proposals for additional assets to provide near-continuous contact between the surface of Mars and Earth. They include the Mars Areostationary Relay Satellite (MARSat) and the 2007 (Agenzia Spaziale Italiana) ASI/NASA Marconi mission.

Abraham [2] has made a compelling case for maintaining equivalent 70-m long-term capability. He analyzed aggregate future mission demographics and identified four key trends:

- Growth of proximity links and consequent “trunk-line” demand
- Migration of NASA's Space Science Enterprise mission set into deep space

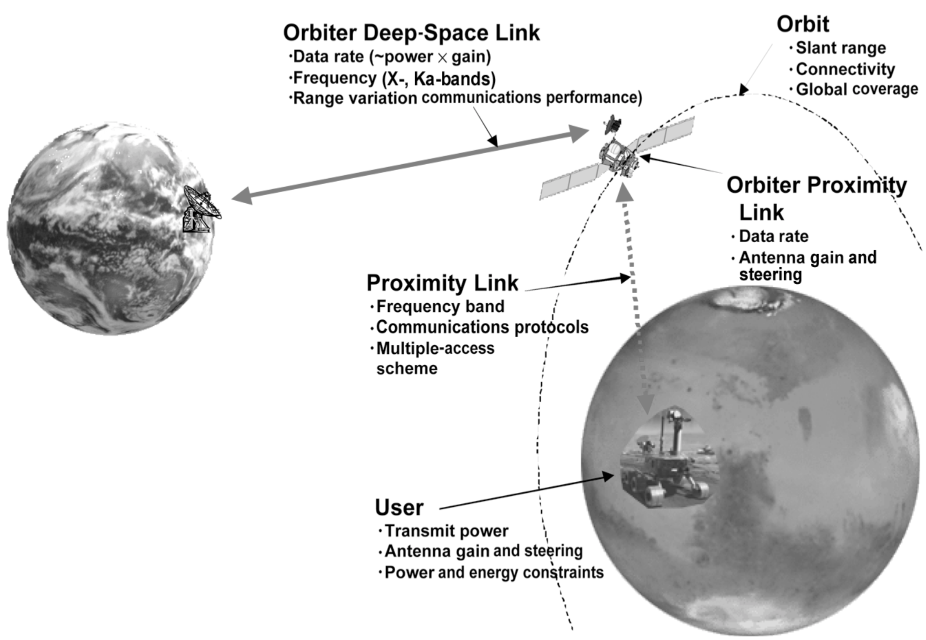

Fig. 10-1. Key considerations for telecommunications relay-system design.

- Mission plan reliance on large-aperture ground stations
- Evolution toward more data-intensive instruments and media.

Nonetheless, the present DSN capability places severe constraints on deep-space science due to data-rate limits, spacecraft antenna and power requirements, and cost. The DSN's current facilities are aging and costly to maintain, while demand is increasing for more complex and data-rich missions. Optical technology, which has limitations due to pointing requirements and high quantum-limited noise, is also being developed. It is not an either/or proposition, however. There is likely to be a continued need for an RF link from the ground for the foreseeable future.

It is exciting to speculate what a 100-fold increase in aperture size could do for space science or spacecraft design, including possibly enabling missions not yet envisioned. However, the only way to accomplish such an increase is through the use of arrays of low-cost, modest-sized reflector antennas. The radio astronomy community believes that

> a revolutionary new instrument at radio wavelengths is [possible], one with an effective collecting area more than 30 times greater than the largest telescope ever built. Such a telescope could reveal the dawn of galaxy formation, as well as a plethora of other new discoveries in all fields of astronomy. Vigorous technological developments in computing and radio frequency devices make it possible for such a telescope to be built within the next decade, and the international radio astronomical community is proposing that such a telescope, with 1,000,000 m^2 of collecting area, be the next major radio telescope to be built [9].

Completion is currently scheduled for some time between 2010 and 2020. The project is called the Square Kilometre Array (SKA).

10.3 Final Thoughts

Radio frequency design of the large antennas of the Deep Space Network has been a great success story. They have seen a significant evolution in performance over the last four decades. Sizes have increased from 26 to 70 m, efficiencies have been enhanced through dual-reflector shaping, and operating frequencies have evolved from L-band to S- and X-bands, to a plan for Ka-band. There has also been a growth from single-frequency to multiple-frequency operation. In addition, operability and maintainability have been enhanced through the use of beam-waveguide designs. However, designs have developed and matured to a point where only very small improvements in performance are possible, especially at S-band and X-band. In fact, virtually the only option available to improve performance at S- and X-band would be to use a clear-aperture antenna such as the Green Bank Telescope (West Virginia) [10]. However, this is a very expensive and mechanically complicated alternative that increases gain by only a fraction of a decibel (or possibly by 1 dB in gain over temperature, or *G/T*). Consequently, it would be far more cost effective to just make the blocked aperture larger. On the other hand, at Ka-band, there is room for improvement in surface accuracy and in gravity-deformation performance.

If the DSN would like a ten- to one-hundredfold improvement in *G/T* performance, it will have to follow the lead of the designers of the next generation of large radio telescopes, who all plan to use large numbers of smaller antennas.

References

[1] S. Brunstein, “Comparison of Implementation Costs Between a 70 m BWG DSS with an Array of Four 34m BWG Antennas,” JPL Interoffice Memorandum 3330-90-116 (internal document), Jet Propulsion Laboratory, Pasadena, California, September 4, 1990.

[2] D. Abraham, “User/Mission Requirements (August 4, 2000),” (JPL internal website), http://eis.jpl.nasa.gov/antrep70m Accessed February 2002.

[3] J. Dreher, “The Allen Telescope Array,” presented at SKA: Defining the Future, Berkeley, California, July 9–12, 2001, http://www.skatelescope.org/skaberkeley/html/presentations/pdfbytopic.htm Accessed February 2002.

[4] P. S. Kildal, L. Baker, and J. Hagfors, “Development of a Dual-Reflector Feed for the Arecibo Radio Telescope: An Overview,” *Antennas and Propagation Magazine*, vol. 33, pp. 12–18, October 1991.

[5] V. L. Krabbendam, T. A. Sebring, F. B. Ray, and J. R. Fowler, “Development and Performance of Hobby Eberly Telescope 11 meter Segmental Mirror,” *SPIE Conference on Advanced Technology Optical/IR Telescopes* VI, Kona, Hawaii, March 1998.

[6] B. Peng, R. Nan, R. G. Strom, B. Duan, G. Ren, J. Zhai, Y. Qiu, S. Wu, Y. Su, L Zhu, and C. Jin, “The Technical Scheme for FAST,” *Perspectives on Radio Astronomy-Technologies for Large Antenna Arrays*, A. B. Smolders and M. P. van Haarlem (eds.), Netherlands Foundation for Research in Astronomy, 1999.

[7] W A. Imbriale, S. Weinreb, V. Jamnejad, and J. Cucchissi, “Exploring the Next Generation Deep Space Network,” 2002 IEEE Aerospace Conference, Big Sky, Montana, March 9–16, 2002.

[8] C. D. Edwards, J. T. Adams, D. J. Bell, R. Cesarone, R. DePaula, J. F. Durning, T. A. Ely, R. Y. Leung, C. A. McGraw, S. N. Rosell, "Strategies for Telecommunications and Navigation in Support of Mars Explorations," *Acta Astronautica*, vol. 48, no. 5–12, pp. 661–668, 2001.

[9] The Square Kilometre Array Website, http://www.skatelescope.org/ Accessed November 2001.

[10] 100-meter Green Bank Telescope [National Radio Astronomy Website], http://info.gb.nrao.edu/GBT/GBT.html Accessed February 2002.